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On Some Properties of a Minimal Flow : A Topological Characterization of the Strict Ergodicity (Random Systems and Dynamical Systems)

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CITATION:

ISHII, I. On Some Properties of a Minimal Flow : A Topological Characterization of the Strict Ergodicity (Random Systems and Dynamical Systems). 数理解析研究所講究録 1981, 439: 128-133

ISSUE DATE:

1981-10

URL:

<http://hdl.handle.net/2433/102792>

RIGHT:

On some properties of a minimal flow

— A topological characterization of the strict ergodicity —

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1. Introduction.

A flow ϕ_t ($t \in \mathbb{R}$) on a compact metric space M is said to be minimal, if M is equal to the orbit closure of each of its points. In the following, we always assume that our flow ϕ_t is a minimal flow on M . ϕ_t is called strictly ergodic, if it admits a unique normalized invariant Borel measure. In [1], Oxtoby has given some nice characterizations of the strict ergodicity (see Theorem A below).

It is known that ϕ_t is Lyapunov-stable if and only if ϕ_t has a unique normalized invariant measure μ and the unitary operator U_t in $L_2(M, \mu)$ defined by $U_t f = f \circ \phi_t$ has pure point spectrum. As is implied by this example, some metrical property can be characterized by a topological property. The Oxtoby's characterization of the strict ergodicity seems not to be purely topological. And so, in what follows, we shall try to give a purely topological characterization of the strict ergodicity.

2. Known results.

By $C(M)$ we denote the set of real valued continuous functions on M . And for $f \in C(M)$, we define $M(f, m, T)$ and $M(f, m)$ ($m \in M, T \in \mathbb{R}$) as follows:

$$M(f, m, T) = \frac{1}{T} \int_0^T f(\phi_t(m)) dt, \quad M(f, m) = \lim_{T \rightarrow \infty} M(f, m, T).$$

A point $p \in M$ is called quasi-regular, if $M(f, p)$ is defined for every $f \in C(M)$. And by Q we denote the set of all quasi-regular points. Oxtoby's characterization is the following.

THEOREM A. ([1]) For a minimal flow (M, ϕ_t) , the following three conditions are equivalent.

- (i) ϕ_t is strictly ergodic.
- (ii) $Q = M$.
- (iii) $M(f, m, T)$ ($T \rightarrow \infty$) converges uniformly on M to a constant for each $f \in C(M)$.

It is known (see [1]) that for each $p \in Q$ there is a unique normalized invariant measure μ_p such that

$$M(f, p) = \int_M f d\mu_p$$

for any $f \in C(M)$. The following theorem of Schwartzman gives a relation between this invariant measure μ_p and the "asymptotic cycles".

THEOREM B. ([2]) For any $p \in Q$ and any $g \in C(M, S^1)$,

$$A_p(g) = \int_M A_m(g) d\mu_p(m),$$

where $C(M, S^1)$ ($S^1 = \{z \in \mathbb{C}; |z| = 1\}$) is the set of S^1 -valued continuous functions, and $A_m : C(M, S^1) \rightarrow \mathbb{R}$ ($m \in M$) is defined by

$$A_m(g) = \lim_{T \rightarrow \infty} \frac{1}{2\pi T} (\arg(g(\phi_T(m))) - \arg g(m)) .$$

From these two theorems, it follows that if ϕ_t is strictly ergodic, then $A_m(g)$ does not depend on m .

3. Topological characterization of the strict ergodicity.

In this section, we assume that M is an n -dimensional smooth manifold and ϕ_t is a smooth minimal flow on M . An open submanifold Σ with codimension one is said to be a local section if it does not contact with the flow everywhere. Moreover we call Σ a δ -local section ($\delta > 0$) if the mapping h defined by $h(m, t) = \phi_t(m)$ is a homeomorphism from $\overline{\Sigma} \times (-\delta, \delta)$ onto $\bigcup_{-\delta < t < \delta} \phi_t(\overline{\Sigma})$. For two δ -local sections Σ_1 and Σ_2 , we define a subset $K(\Sigma_1, \Sigma_2)$ of Σ_1 to be

$$K(\Sigma_1, \Sigma_2) = \{m \in \Sigma_1; \int_0^t (\chi_1(\phi_t(m)) - \chi_2(\phi_t(m))) dt > c > -\infty \text{ for any positive } t\} ,$$

where χ_j is the characteristic function of $\bigcup_{0 < t < \delta} \phi_t(\Sigma_j)$. It can be shown that if $K(\Sigma_1, \Sigma_2)$ is neither empty nor Σ_1 , then it is a countable union of nowhere dense closed subset of Σ_1 . With this definition we can give a topological characterization of the strict ergodicity as the following.

THEOREM C. ϕ_t is strictly ergodic if and only if the following condition (*) is satisfied:

(*) whenever $K(\Sigma_1, \Sigma_2)$ is neither empty nor Σ_1 , for any compact subset K of $K(\Sigma_1, \Sigma_2)$ and for any local section Σ , there is a bounded function $F: K \rightarrow \mathbb{R}$ such that $\hat{F}(K) \subset \Sigma$ and \hat{F} is injective ($\hat{F}(m) = \phi_{F(m)}(m)$).

Moreover we can prove that

THEOREM D. If ϕ_t is not strictly ergodic, then for any normalized invariant Borel measure μ there are δ -local sections Σ_1 and Σ_2 such that $K(\Sigma_1, \Sigma_2) \neq \emptyset$, Σ_1 and $\mu(\bigcup_{0 < t < \delta} \phi_t(K))$ is positive for some compact set $K \subset K(\Sigma_1, \Sigma_2)$.

In the following, we shall give an outline of the proof of Theorem C. First we state a lemma.

LEMMA. For any local section Σ we can construct a minimal flow $\tilde{\phi}_t$ on a compact metric space \tilde{M} which has the following properties:

- (i) $\tilde{\phi}_t$ is an extension of ϕ_t , namely there is a continuous map $p: \tilde{M} \rightarrow M$ such that $p \circ \tilde{\phi}_t = \phi_t \circ p$,
- (ii) $\tilde{\Sigma} = p^{-1}(\Sigma)$ is a cross-section of $\tilde{\phi}_t$,
- (iii) to each invariant measure $\tilde{\mu}$ of $\tilde{\phi}_t$, there corresponds an invariant measure μ of ϕ_t such that $\mu = \tilde{\mu} \circ p^{-1}$ and this correspondence is one-to-one.

For the method for constructing such a minimal flow, one should refer to [3].

Outline of the proof of THEOREM A.

(Sufficiency) By the lemma, it is sufficient to show that the Poincare-map T induced by ϕ_t on the cross-section Σ has a unique normalized invariant Borel measure. The condition (*) implies that T has an invariant measure ν which satisfies that $\nu(p^{-1}(\Sigma_1)) = \nu(p^{-1}(\Sigma_2))$ (Σ_1 and Σ_2 are open subsets of Σ) if and only if $K(\Sigma_1, \Sigma_2) \neq \emptyset$, Σ_1 or $K(\Sigma_1, \Sigma_2) - \Sigma_1 = K(\Sigma_2, \Sigma_1) - \Sigma_2 = \emptyset$. And moreover we can see that this invariant measure ν is the unique one.

(Necessity) Suppose that $K(\Sigma_1, \Sigma_2)$ is neither empty nor Σ_1 and for some its compact subset there is a local section $\tilde{\Sigma}$ for which there is no bounded function F such that \hat{F} is injective. We can construct a minimal flow (\tilde{M}, ϕ_t) satisfying (i), (ii), (iii) of the lemma so that $\tilde{\Sigma}_j = p^{-1}(\Sigma_j)$ ($j = 1, 2$) are both cross-sections of ϕ_t . Here we define functions τ_j and T_j ($j = 1, 2$) on M as follows:

$$\tau_j(\tilde{m}) = \sup \{ t \leq 0 \mid \phi_t(\tilde{m}) \in \tilde{\Sigma}_j \}$$

$$T_j(\tilde{m}) = \inf \{ t > 0 \mid \phi_t(\tilde{m}) \in \tilde{\Sigma}_j \},$$

and define $f_j : \tilde{M} \rightarrow S^1$ by

$$f_j(\tilde{m}) = \exp(2\pi\sqrt{-1}\tau_j(\tilde{m})/T_j(\hat{\tau}_j(\tilde{m}))), \quad (\hat{\tau}_j(\tilde{m}) = \phi_{\tau_j(\tilde{m})}(\tilde{m})).$$

Because $\tilde{\Sigma}_j$ is a cross-section, f_j is continuous. Then, according to the assumption on Σ_j , we can see that for $f = f_1/f_2 \in C(\tilde{M}, S^1)$, $A_{\tilde{m}}(f)$ cannot be independent of \tilde{m} . Hence,

by Theorems A and B, ϕ_t is not strictly ergodic, and so ϕ_t is also not strictly ergodic.

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